Eugene E. Lundquist

ARR No. 5F07

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WARTIME REPORT

ORIGINALLY ISSUED

September 1945 as
Advance Restricted Report 5F07

IMPACT PROPERTIES AT DIFFERENT TEMPERATURES OF FLUSH-RIVETED JOINTS FOR AIRCRAFT MANUFACTURED BY VARIOUS RIVETING METHODS

By G. A. Maney and L. T. Wyly
Northwestern University

NACA

WASHINGTON

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

ADVANCE RESTRICTED REPORT

IMPACT PROPERTIES AT DIFFERENT TEMPERATURES OF FLUSH-RIVETED JOINTS FOR AIRCRAFT MANUFACTURED BY VARIOUS RIVETING METHODS

By G. A. Maney and L. T. Wyly

SUMMARY

The results of an investigation to determine the impact properties of flush-riveted joints manufactured by different riveting methods are presented. Tests were made on a pendulum impact machine at temperatures of 70°, -50°, and -70° F. The rivets were made of aluminum alloy A17S-T and the plates, of aluminum alloy 24S-T. Preliminary tests at 70° F on specimens having varying ratios of rivet diameter to plate thickness were made under both static and dynamic loads. Supplementary torsion impact tests at 70° and at -70° F were made on specimens of 17S-T aluminum alloy obtained commercially. A metallographic study and some photomicrographs of the metal are included.

The results of the tests showed the joints to be stronger under impact loads at temperatures varying from -50° to -70° F than at 70° F. No appreciable difference was found in the impact strength from -55° to -70° F. Torsion impact tests on commercially obtained specimens of aluminum alloy 17S-T showed about 10-percent increase in shear strength at temperatures of -70° F as compared with that obtained at 70° F. Commercial countersunk rivets with the head 0.003 inch below the surface before driving produced the strongest joints under impact load. Reverse-driven rivets (method E) produced the weakest joints for impact loads. Correlation of the impact energy to rupture with the area under the static load-deformation curve made in some preliminary tests showed remarkably consistent and fairly close agreement. There is a complete lack of correlation between the static strength of the joints and their capacity to absorb energy. The use of larger rivets in a given plate increases the energy

absorption for the reason that the stronger rivets cause the plates to absorb energy by local buckling and distortion before the rivets shear. This property appears to be of considerable significance and worthy of a more detailed investigation.

INTRODUCTION

Tests by Johnson and Oberg (reference 1), by Templin and Paul (reference 2), and by others have shown that aluminum alloys develop greater strength, both in impact at notches and in tension, at low temperatures than at 70° F.

So far as is known, no results of low-temperature impact tests on riveted joints of the type presented herein are available, and this study was undertaken to provide some information on the subject. After some preliminary study, it was decided to limit the scope of the investigation to one size of rivet, one thickness of plate, one type of specimen, and four methods of riveting. (See fig. 1.)

The present study was made at the Technological Institute, Northwestern University, under contract to the NACA. The methods of riveting investigated are those for which static strength has been investigated by the Langley Memorial Aeronautical Laboratory of the National Advisory Committee for Aeronautics. (See reference 3.) The work was conducted under the direction of the authors.

Credit for performing the actual tests should be given to the following students: Eugene Kalinowski, Kenneth Lenzen, Gordon Olson, and Allin Schweitzer. The thermocouple measurements were made by Mr. J. B. Sutherland, Assistant Professor of Chemical Engineering. The metallographic examinations and report were made by Mr. V. C. Williams, Associate Professor of Chemical Engineering, assisted by Mr. Sutherland.

APPARATUS AND METHODS

Riveting methods.- The methods of riveting used are those developed by the Langley structures research laboratory of the NACA and described in reference 3. The types of rivets used and their dimensions, the angles of the countersunk holes, and the side from which the rivets are inserted are shown in figures 2 to 5. The distinguishing features of the riveting methods used in this investigation are:

Method C. The manufactured head of the countersunk rivet is driven with a vibrating gun, while the shank end is bucked with a bar. The driven rivet head is flat. All specimens riveted by this method are given the prefix C in the designation.

Method N. The manufactured round head of the rivet is driven with a vibrating gun, while the shank end is bucked with a bar. After the rivet is driven, the portion of the formed head that protrudes above the skin surface is milled off and finished smooth with the sheet. All specimens riveted by this method have the prefix N.

Test specimens.- Details of the specimens for the Preliminary Tests are shown in figure 6. Details of the specimens for the Main Tests are shown in figure 1. The preliminary specimens were detailed by the University. The Langley Memorial Aeronautical Laboratory made the final details of the main test specimens and furnished all specimens for both preliminary and regular tests.

Materials.- The plates were made from sheets of 24S-T aluminum alloy. The rivets were made from A17S-T aluminum alloy.

Specimen grips.- The grips used to mount the specimens in the testing machines are split screw fittings which were secured to the ends of the specimens by drive fit dowels, by friction, and by split tapered dowels. Details are shown in figure 7.

Testing machines.- The preliminary static tests were run on a Southwark-Emery universal hydraulic testing machine having a capacity of 120,000 pounds. This machine is equipped with two low-range-loading scales of 0 to 600 pounds and of 0 to 6000 pounds and is accurate to within 0.25 percent. Pacing disks enable the operator to control rate of loading as desired. Figure 8 is a photograph of this machine.

All dynamic tests were run on a Riehle pendulum impact machine (fig. 9) having a capacity of 220 foot-pounds, which is equipped for tension impact testing. The weight of the pendulum hammer is 43.26 pounds, the radius to the striking edge (center of percussion) is 31.50 inches, the maximum height of vertical drop is 5.085 feet, and the maximum capacity is 220 foot-pounds. The energy of rupture of the specimen is read on an engraved plate attached to the machine. This machine is practically frictionless, and the calibration is very accurate.

Temperature control.- The room-temperature tests were run in the University Materials Testing Laboratory where the temperature is quite constant. The low-temperature tests were run in the cold room of the Mechanical Engineering Department, which is large enough to accommodate sizeable setups and in which temperatures as low as -70° F and lower can be maintained indefinitely. A continuous record of room temperature is provided on a recording chart. This recorder has been calibrated by thermocouples and alcohol thermometers and was found to be accurate to within 1° F.

PRELIMINARY TESTS

The preliminary tests were made to investigate:

1. The strength of the shank of the specimen for the purpose required

2. The possibility of a slip between the specimens and the grips

3. The effect of striking velocity of the pendulum hammer on the energy of rupture

4. The manner of failure of the riveted joints

5. The relation, if any, between the energy of rupture and the area under the load-deformation curve

The specimens in these preliminary tests were of two plate thicknesses (0.04 and 0.064 in.) and of two rivet sizes (3/32- and 1/8-in. diameters) and riveting was by method C (with $h_b = 0$) and by method E.

Preliminary Test Procedure

The procedure in the static tests was to mount a Moore-type extensometer on the specimen, the upper half of the instrument being fastened to one plate and the lower half to the other plate, so that dial movement registered total shearing deformation of the rivet shanks in shear. The set-up is shown in figure 10. The specimens were mounted in self-centering grips. All loading was very slow to allow time for study of behavior. In this report the yield load is defined as the shear load per rivet at which the measured displacement is 4 percent of the rivet diameter.

The pendulum impact machine used (fig. 9) is equipped for tension impact testing, and the rivets were tested in shear by mounting a special striking bar on the split screw grips. (See fig. 11.)

Preliminary Test Results

Strength of shank.- No weakness in the shanks of the specimens was discovered in any of the tests.

Slip in grips.- Three static tests were run to check for possible slip of the plates in the split screw fittings, and instruments were used to compare the over-all movement between grips against the movement of one specimen plate with respect to the other. These tests were run on specimens O2B, N1A, and N4A and established the fact that no appreciable slip was occurring between the specimens and the grips. At least half of the slight discrepancy of movement between the grips and the specimen plates probably is due to stretch in the specimen shanks between grips and the strain-gage attachment. The total area under the two curves is nearly the same. Careful examination of the specimen before and after rupture in the impact machine indicated that no discoverable slip had occurred there.

Effect of velocity.- Every precaution was taken in running the impact tests to insure that there was no appreciable loss of energy due to slip of the specimens in the adapters or to other sources. The adapters were screwed tightly into the pendulum hammer and into the striking bar, thin washer shims being used as necessary to keep the contact plane of the two plates of the specimen in a vertical plane. The striking bar and specimen were so adjusted prior to test that the bar hit in the center of both anvils at the same time.

In the preliminary tests similar specimens were tested at speeds of pendulum hammer at time of impact of 4.6 feet per second and of 18.1 feet per second without any appreciable variation in energy of rupture. Inasmuch as the sensitivity of load indication on the machine plate was greater at lower speeds, it was decided to run the tests at 2.11 and 2.44 feet per second. Also, it seemed more likely that slower speeds would more nearly approach operating conditions of impact loads on these joints in service. No information was available regarding the "transition" or "critical" speed of loading for the metal used in these tests but, if there is such a limiting speed, it is evidently greater than 18 feet per second. (See reference 4.)

The energy to rupture of these specimens was of the order of 4 foot-pounds or less. In order to secure a maximum horizontal distance of travel for the small vertical distance required and, hence, maximum sensitivity of energy indication on the scale, the position of the pendulum hammer at time of release was made near the bottom of the arc of hammer swing and was such that the available kinetic energy of the pendulum at the instant of impact was either 3 or 4 foot-pounds. This initial pendulum position was determined experimentally by inserting a block of proper length between the hammer disk and the machine frame and releasing the pendulum by suddenly jerking the block out of place. The maximum error in energy of rupture thus determined is less than 5 percent. This procedure was used for all tests after the two trials at higher speed.

Manner of failure.- In order to investigate the manner of failure of the joints careful investigation was made of the action during slowly applied static loads. Two extremes of behavior were found. The combination of a thick plate and a small rivet with the countersunk head used produced an almost perfect shearing test on the rivets; no evidence of distortion or rotation of the rivet other than shear and no evidence of distortion of the plate were visible to the naked eye. The fracture of the rivet exhibited a clean shear surface uncut by the sharp edge of the countersunk plate. The other extreme was the combination of the thin plate with a large rivet which behaved quite differently. At a fairly high stress, the edges of the countersunk head would curl, and this effect was accompanied by such a rotation of the rivet in the joint that thereafter the rivet was partly in shear and partly in tension. The rotation allowed the sharp countersunk edge of the plate to cut into the rivet shank and also resulted in local deformation of the plate in crushing and bending. The fracture of these rivets exhibited a surface partly cut through by the sharp edge of the plate and partly sheared. (See figs. 12 and 13.) The specimens having combinations of plate rivet sizes between these extremes exhibited intermediate degrees of local deformation, as would be expected, with intermediate ultimate loads.

Investigation of similar specimens after rupture in the impact machine showed that the results obtained in static failure were also found in impact failure.

Quite naturally, and most interestingly, the specimens exhibiting local rivet and plate deformation developed much greater impact-rupture energies than the specimens which failed by pure shear in the rivets. (See table 1 and figs. 14 and 15.)

Static load and impact energy.- A number of specimens were tested statically to investigate the relation between static load and impact energy to rupture, and the load deformation curves are shown in figures 16 to 19. It was found that remarkably good agreement existed between the energy given by the area under the load-deformation static curve and the energy to rupture in the impact machine. (See table 1.) No attempt was made to measure heat loss due to friction between the plates or due to flow of the rivets in shear. A quantitative measurement of the lost energy due to internal flow and dissipated in heat in a static tension test is given by Haskell (reference 5). This information goes far toward explaining the recognized discrepancy between energy loads of rupture for the impact and static loading of ductile materials. However, the discrepancy between the energy to rupture of the static and impact loads for the specimens tested is of about the same order as the discrepancy between either the ultimate static load or the impact energy required to break two similar specimens. It is thought that the heat loss in the riveted specimens of this series is relatively small.

Discussion of Preliminary Test Results

The close correlation between the static and impact energies for rupture found in these tests is most interesting. The results are so consistent that there can be no doubt of the agreement indicated. This correlation means that the impact-rupture loads for such joints in shear may be obtained from carefully run static tests. It should be emphasized that the velocities used in these tests were low and throw no light on the shear strength of the material at speeds above the transition speed under high-velocity impact loads.

Quite striking is the effect upon rupture energy of varying the ratio of rivet diameter to plate thickness. As the rivet diameter is increased for a given plate thickness so that more local deformation of the platé precedes rupture of the rivets in shear, the energy absorbed by the total unit rises rapidly. In order to show this condition graphically, attention is called to figures 15 and 20. It is seen that the static strength varies directly as the cross-sectional areas of the rivets; whereas the impact strength increases rapidly as the ratio of diameter of rivet to plate thickness rises. Thus, for a given plate thickness of 0.04 inch, replacing a 3/32-inch rivet by a 1/8-inch rivet will increase the static strength by about 80 percent, but will increase the dynamic strength by about 300 percent. These relations are shown in a more general way in figure 14 where the ordinates represent energy of rupture divided by the rivet diameter times plate thickness, and the abscissas represent the ratio of rivet diameter to plate thickness. This method of plotting the ordinates is equivalent to assuming that the energy of rupture is distributed over a width equal to the rivet diameter, or some constant percentage of the rivet diameter. Obviously, the problem is not so simple as this reasoning indicates, but the assumption appears to give a fair representation of the relation of the variables. Plainly, there is an upper limit of the d/t ratio for static strength, that is, the buckling strength of the plate back of the rivet. This relation for structural nickel steel was determined experimentally in studies for the Quebec Bridge (reference 6). (See fig. 21.) It is, however, evident that this limiting ratio of d/t has not been reached in the specimens tested, since there is no dropping off in static yield strength with the larger d/t ratios. (See fig. 14(a).)

This relation appears to be of direct interest to designers of aircraft. Increase of rivet diameter used in a given plate will not reduce static strength or fatigue strength and will greatly increase strength under energy loadings. This conclusion is so interesting in its implications that there is an apparent need for a comprehensive series of tests of impact and fatigue strengths of riveted joints with varying ratios of rivet diameter to plate thickness.

MAIN TESTS

In the main test series all specimens were broken in the pendulum impact machine, half at room temperature and half at sub-zero temperature. All rivets were 3/32 inch in diameter and all plates were 0.064 inch thick. Four methods of riveting were used: Method C with $h_b = 0.010$, $h_b = 0.000$, $h_b = -0.003$ inch, and method E. Five specimens for each type of riveting, or a total of 20 specimens, were tested at 70° F, and a like number were tested at temperatures varying from -50° to -70° F.

The principal questions to be investigated in this series were:

1. The relative strength of the four different methods of riveting under impact loads

2. The effect of varying the temperature between -55° and -71° F

3. The relative strength of the methods of riveting at room temperature and at low temperatures

Main Test Procedure

The procedure for the main tests was the same as that developed in the preliminary tests, the striking velocity of the hammer being about 2 feet per second.

The pendulum machine is practically frictionless at normal temperatures, and no measurable error can be found in the graduated dial. For tests in the cold room, several special lubricants for the ball bearings were tried, and kerosene oil was finally selected. At temperatures of -50° to -70° F a slight amount of friction was found in the bearings. This friction amounted to less than one-half of 1 percent and was found to be constant. The machine was checked for friction before and after each individual test.

Several days before the low-temperature tests were started, the testing machine, specimens, and all tools to be used were placed in the cold room. At the time of starting the actual testing, the room and all its contents had been held at a temperature of -66° F for over 24 hours. The work was done by two men working together in the cold room, clothed in regulation flying suits. It was necessary to remove the split-screw fittings from a broken specimen before placing them on the unbroken specimen, and this work was done in the cold room, the men using woolen gloves lined with silk for this operation. In order to determine how long the specimen should stand in the machine after being handled in order that its temperature be that of the room, some thermocouple studies were made at various room temperatures. The results of one such study are shown in figure 22.

Main Test Results

The results for the main tests are shown in table 2 and in figure 23. They are summarized in table 3. The curve for energy to rupture at low temperatures in figure 23 shows a general variation with values of h_b similar to the curve for tests at ordinary temperatures (70° F) with the specimens riveted according to method E showing lowest strength.

This increase in strength of the joint with reduction of the value of h_b for method C is seen to be remarkably regular and to confirm the theory that, as the rivet is reduced in size so that it can deform in addition to failing in shear, it absorbs additional energy by such deformation. The relation holds both at room temperature and at low temperatures. The specimens riveted by method E are thus seen to correspond in stiffness to a specimen riveted by method C with h_b equal to about 0.013 inch.

The increase in impact strength from $h_b = 0.010$ to $h_b = -0.003$ is about 45 percent at room temperature and about 15 percent at low temperature, but the total increase in strength is more nearly the same, being 0.20 foot-pounds for room temperature and 0.13 foot-pounds for low temperatures.

No appreciable difference was found in the results at -55° and at -70° F. No other low temperatures were used in this series.

The joints tested at low temperatures exhibited a marked increase in impact strength over the strength at ordinary temperatures, the amount varying from about 60 percent for method C with h_b equal to -0.003 inch to about 120 percent for method E. Johnson and Oberg (reference 1), Templin and Paul (reference 2), Rosenberg (reference 7), and others have shown that aluminum alloys increase in strength in static tensile tests and in notched-bar impact tests at low temperatures, but the percentage of increase reported has been of the order of about 10 percent.

Discussion of Main Test Results

The increase in impact strength as the value of h_b is reduced is consistent with the principles of mechanics and with the results of previous static tests by Lundquist and Gottlieb (reference 3). The graphs for specimens riveted by method C in the report by these investigators show that, although the ultimate static strength does not change greatly as h_b varies, the yield strength decreases and the area under the load-deformation curve increases rapidly as h_b is reduced. (See figs. 10 to 13 of reference 3.)

The most outstanding result of these tests was the remarkable increase in impact strength noted at low temperatures. The constant care used in the testing work, the smoothness of the curves in figure 23, and the narrow spread of the individual results shown in table 3 would seem to preclude possibilities of serious error in the testing procedure.

Careful examination of the contact surfaces of the plates failed to disclose any variation in smoothness or surface conditions of the different specimens that might affect the strength of the joint by friction. Also, all available information regarding the variation of the coefficient of thermal expansion between the plate and the rivet materials indicated no substantial effect on clamping force from temperature change.

It is to be noted that specimens C2 in the preliminary tests are stronger than the same type of specimens CB in the main test series. Examination disclosed that the bucked heads (i.e., the heads upset by bucking bar in driving) are higher and less wide in the case of the C2 specimens. A check of the rivet heads of the main-test-series specimens, however, showed no such variation between any of the rivets.

Impact strength (i.e., the ability to absorb energy) of a material appears to be largely a function of distortion in shear, the contribution of cohesive strength being relatively small. Hence, those factors which tend to increase ductility and reduce brittleness will promote impact strength. These factors are the following:

1. Uniaxial stress rather than multiaxial stress

2. Rate of loading

3. Temperature of the material

4. Internal structure of material

Some recent valuable studies on this subject are the papers by Ludwik (reference 8), McAdam and Clyne (reference 9), and by Jones (reference 10).

There is no reason to believe that the stress distribution in the specimens of this series tested at low temperature differs from that in the specimens tested at room temperature.

Johnson and Oberg (reference 1), Templin and Paul (reference 2), and Rosenberg (reference 7) report on impact tests of aluminum alloys at low temperatures. A summary of available studies is given in Gillett's report (reference 11). In all tests reported by these writers, the striking velocity of hammer was not greater than 18 feet per second. If there is a critical velocity for impact strength of the rivet material, it is evidently greater than this value. The preliminary tests reported herein showed no appreciable difference in impact strengths for those specimens for velocities of 2 or 4 feet per second and 18 feet per second.

The tests reported in the previous paragraph all show some increase in strength for impact tests at low temperatures on notched-bar specimens of aluminum alloys. For example, Rosenberg made tests on a variety of aluminum alloys at temperatures ranging from 20° to -78° C (a range far exceeding temperatures used in the present series), and his results are graphed in figure 23 of reference 7, page 699. No evidence is shown by any of these tests indicating a transition temperature zone for these materials.

No detailed information regarding the material used in the rivets in these specimens furnished by the NACA was immediately available. Also, very little work appears to have been reported on the effect of heat treatment on the low-temperature impact strength of the aluminum alloys. In an effort to discover the reason for this marked increase in impact strength at low temperatures, three supplementary investigations were made.

SUPPLEMENTARY TESTS

Torsion Impact Tests of 17S-T Aluminum Alloy at 70° and -70° F

No information was found on shear tests of aluminum alloy 17S-T at low temperatures but, since the tension specimens fail in shear, the conclusion would follow that the increase in shear strength at low temperatures would be of about the same order as the increase in tensile strength. However, it was decided to make some shear tests using the method of reference 12, which were run on a Carpenter torsion impact machine (fig. 24). This machine ruptures a round specimen by twisting impact, and the energy of rupture is measured by drop in revolutions per minute of the flywheel.

The specimens were made from aluminum alloy 17S-T commercially obtained and were tested at 70° F and at -70° F. The results and details are shown in table 4. There was a slight difference in the dimensions of the different specimens, and the comparison was made accordingly on the basis of modulus of toughness obtained by dividing the energy of rupture by the volume of the metal which had been distorted in twisting. It was necessary to replace all lubricant on all parts of the machine by a thin film of kerosene oil and to place the tachometer on the machine just before the test. At the time of test, the specimen and the machine had been held at a low temperature for 2 days and had been held at -70° F for over 12 hours. It will be noted that the strength in torsion impact at -70° F is about 10 percent greater than at 70° F, a result consistent with information obtained by other investigators but throwing no light on the much greater impact strengths found at low temperatures in the joints tested herein. In short, this investigation indicated that the increased impact strength of the joints was not solely due to testing at low temperatures.

Metallographic Examination of Rivet Material

A metallographic investigation of the rivet material was next made. This work was done by Professor V. O. Williams of the Department of Chemical Engineering of Northwestern University and his report follows:

I. Specimens.

Four specimens were submitted, which were prepared for metallographic examination. The samples were CC5 which had been tested at 70° F, CC8 which had been tested at -70° F, and supplementary specimens 1 and 7 (table 4), which had been tested at 70° F and -70° F, respectively. Specimens 1 and 7 were tested in a torsion impact machine and were examined in a plane longitudinal with the axis. Specimens CC5 and CC8 were sheared by impact in a Riehle machine and were examined perpendicularly to the axis of rupture. Specimens 1 and 7 were 17S-T aluminum alloy, and specimens CC5 and CC9 were rivet specimens with A17S-T rivets in 24S-T aluminum-alloy sheet.

II. Treatment.

The samples were mounted and ground and polished in the usual manner. Etching was done by the two-etch technique of the Aluminum Company of America using 25 percent nitric acid for the first etch and sodium fluoride, nitric acid, and hydrochloric acid for the second etch. All photographs were taken at a magnification of approximately 100 diameters.

III. Interpretation.

According to figures 25(a) and 25(b), which are photomicrographs of specimens 1 and 8, respectively, there is no particularly great difference between the microconstituents; both are well-treated 17S-T aluminum alloy with complete intragranular precipitation of the Delta phase. The strength and hardness should be that associated with a good grade of this alloy. In addition, there is apparently no great differentiation with temperature between the microconstituents.

Figures 25(c) and 25(d), specimens CC5 and CC8, show the results of impact testing at 70° F and -70° F, respectively. In both photographs the head of the rivet is at the top and the riveted sheet material is the dark zone in the lower right and left hand corners. There is no effective difference in the sheet material in the two cases. However, the remarkable difference in the shank and head structure in the two cases should be noted. In figures 35(c) and (d) the grain structure of the A17S-T is fully developed and the dark spots inside the grains associated with properties of the Delta phase are well developed. The flow patterns due to driving of the rivet are easily noticed at the top of the photograph. Again there is apparent no great differentiation with temperature between the microconstituents.

A number of photomicrographs were taken of other specimens of the main series with the same results as above.

Tests on Riveted Joints Fabricated at Northwestern University at 70° and -70° F

A third supplementary investigation was made consisting of impact tests at 70° and at -70° F on joints fabricated at Northwestern University. These specimens were made of two flat aluminum-alloy 24S-T plates 1 inch wide and 1/8 inch thick riveted together with two 1/8-inch-diameter rivets of aluminum alloy 17S-T. The riveting was similar to the CB specimens of the main test series. About 60 specimens were tested.

The testing sequence was as follows:

Group 1. Tested at 70° F. Control specimens.

Group 2. Held at low temperature various periods and then tested at low temperature.

Group 3. Held at low temperature various periods and tested at room temperature at various time intervals after removal from cold chamber, the maximum interval being about 28 hours.

Considerable increase in impact strength was found for all joints which had been subjected to the low temperature treatment, and this held for the specimens which had been at 70° F for 28 hours after removal from the low temperature chamber. In no case, however, was this increase in strength nearly so large as that shown by the main test series, although the increase was larger than that reported in references 1, 2, and 7. Also the variation in the results was much greater than in the case of the main test series.

Photomicrographs of this series also failed to show any any marked change in internal structure.

Discussion of Supplementary Test Results

The authors have no detailed information regarding the original physical properties of the rivet material or its history but, presumably, the principal difference between the material in the rivet stock and the torsion specimens is the greater amount of cold work received by the rivets at the time of driving. The technique of so-called low-temperature tempering and stabilizing of special steels has been developing rapidly. (See references 13 and 14.) In these references the purpose has been to complete the transformation of austenite into martensite, securing increased hardness, greater ductility, and more toughness.

The authors strongly recommend that a special investigation be made to ascertain the fundamental relations involved and to learn the degree of change in the physical properties possible, the stability of such physical changes and the technique of securing the desired improvements.

GENERAL CONCLUSIONS

The following general conclusions are drawn from the results of the investigation to determine the impact properties of flush-riveted joints for aircraft manufactured by different riveting methods:

1. The energy required to rupture riveted joints of the type tested under impact loads where the striking velocity does not exceed about 18 feet per second may be obtained from the area under the load-deformation curve for static tests.

2. The energy to rupture of joints of the type tested increases very rapidly with the increase of rivet diameter relative to plate thickness; whereas the static unit strength, within the limits tested, increases only in proportion to the cross-sectional areas of the rivets.

3. The strength of the rivet stock tested is increased from 60 to 120 percent when tested at temperatures as low as -50 F. This result should be checked by an independent investigation, and the whole question of low temperature impact strength should be carefully explored.

Northwestern University,
Evanston, Ill., May 1, 1945.

REFERENCES

1. Johnson, J. B., and Oberg, Ture: Mechanical Properties at Minus 40 Degrees of Metals Used in Aircraft Construction. Metals and Alloys, vol. 4, no. 3, March 1933, pp. 25-30.

2. Templin, R. L., and Paul, D. A.: Tensile Properties of Aluminum Alloys at Temperatures below Normal. Joint A.S.T.M.-A.S.M.E. Symposium on Effect of Temperature on the Properties of Metals, 1931, p. 309.

3. Lundquist, Eugene E., and Gottlieb, Robert: A Study of the Tightness and Flushness of Machine-Countersunk Rivets for Aircraft. NACA RB, June 1942.

4. Mann, H. C.: High Velocity Tension-Impact Tests. Proc. A.S.T.M., vol. 36, 1936, p. 85.

5. Haskell, R. K.: True Stress Strain Curves for Polycrystalline Material. Jour. Appl. Phys., vol. 9, no. 1, Jan. 1938, pp. 30-33.

6. Department of Railways and Canals: Final Report of the Government Board of Engineers on the Quebec Bridge, vol. 1, 1919.

7. Rosenberg, Samuel J.: Effect of Low Temperatures on the Properties of Aircraft Metals. Res. Paper RP1347, Nat. Bur. of Standards Jour. Res., vol. 25, no. 6, Dec. 1940, pp. 673-701.

8. Ludwik, P.: Streckgrenze, Kalt- und Warme-prödigkeit. Z.V.D.I., vol. 70, no. 12, March 20, 1926, pp. 379-386.

9. McAdam, D. J., Jr., and Clyne, R. W.: The Theory of Impact Testing; Influence of Temperature, Velocity of Deformation, and Form and Size of Specimen on Work of Deformation. Proc. A.S.T.M., vol. 38, 1938, pp. 112-134.

10. Jones, P. G.: On the Transition from a Ductile to a Brittle Type of Fracture in Several Low-Alloy Steels. Proc. A.S.T.M., vol. 43, 1943, pp. 547-555.

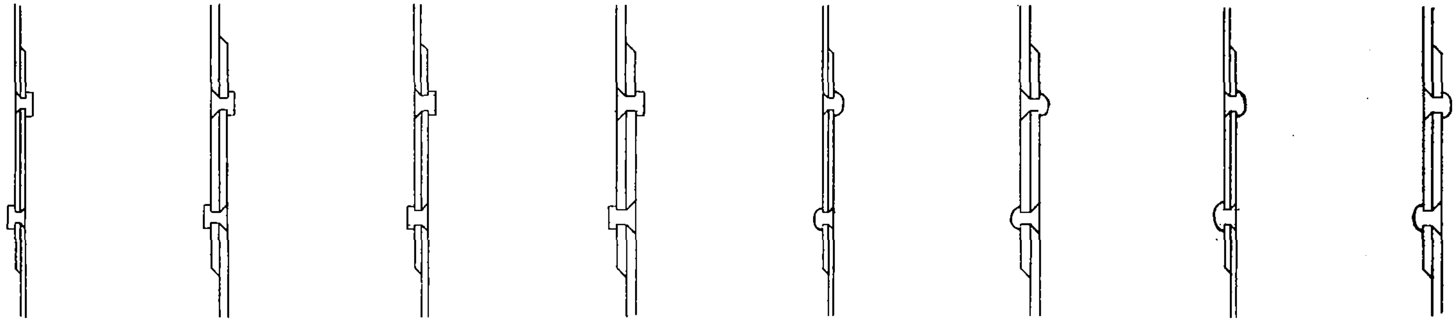
11. Gillett, H. W.: Impact Resistance and Tensile Properties of Metals at Subatmospheric Temperatures. Book prepared for Project 13 of the Joint A.S.T.M.-A.S.M.E. Res. Com. on Effect of Temperature on Properties of Metals. A.S.T.M. (Philadelphia), Aug. 1941.

12. Luerssen, G. V., and Greene, O. V.: The Torsion Impact Test. Proc. A.S.T.M., vol. 33, pt. II, 1933, pp. 315-333.

13. Gordon, P., and Cohen, M.: The Transformation of Retained Austenite in High Speed Steel at Subatmospheric Temperatures. Trans. Am. Soc. Metals, vol. 30, 1942, p. 569.

14. Berlien, G. B.: Subzero Refrigeration: Developing a More Completely Heat Treated Structure. The Tool Engineer, Jan. 1944.

TABLE 1.- RESULTS OF PRELIMINARY TESTS



C1 C2 C3 C4 N1 N2 N3 N4

Specimen	Rivet diam., d (in.)	Plate thickness, t (in.)	Rivet area	Static tests						Impact tests			dt	$\frac{d}{t}$	$\frac{\text{Energy}}{dt}$ $\frac{\text{ft-lb}}{\text{sq in}}$	
				Yield load			Ultimate load			Rupture energy (ft-lb)	Fall of pen-dulum (ft.)	Velocity (fps)			Yield load	Ultimate load
				Total (lb.)	(psi)	Energy (ft-lb)	Total (lb.)	(psi)	Energy (ft-lb)							
Method C																
C1A	3/32	0.04	0.0138	334	24200	0.074	475	34500	1.44	—	—	—	0.00375	2.342	19.8	384
C1B	3/32	.04	.0138	—	—	—	—	—	—	1.0	0.09	2.3	.00375	2.342	—	267
C2A	3/32	.064	.0138	306	22100	.070	490	35500	1.01	—	—	—	.00600	1.465	11.7	168
C2B	3/32	.064	.0138	337	24400	.085	492	35600	0.96	—	—	—	.00600	1.465	14.2	160
C3A	1/8	.04	.0246	468	19000	.141	1009	41100	4.24	—	—	—	.00500	3.125	28.2	848
C3B	1/8	.04	.0246	—	—	—	—	—	—	4.4	.09	2.3	.00500	3.125	—	880
C4A	1/8	.064	.0246	—	—	—	—	—	—	2.0	.34	4.6	.00800	1.953	—	250
C4B	1/8	.064	.0246	—	—	—	—	—	—	2.4	5.08	18.1	.00800	1.953	—	300
Method E																
N1A	3/32	0.04	0.0138	414	30000	0.088	478	34500	0.88	—	—	—	0.00375	2.342	23.5	234
N1B	3/32	.04	.0138	—	—	—	—	—	—	0.8	0.09	2.3	.00375	2.342	—	213
N2A	3/32	.064	.0138	—	—	—	—	—	—	.4	.09	2.3	.00600	1.465	—	67
N2B	3/32	.064	.0138	446	32300	.106	504	36300	.46	—	—	—	.00600	1.465	17.7	77
N3A	1/8	.04	.0246	667	27100	.177	914	37200	2.20	—	—	—	.00500	3.125	35.4	440
N3B	1/8	.04	.0246	—	—	—	—	—	—	3.4	.09	2.3	.00500	3.125	—	680
N4A	1/8	.064	.0246	695	28300	.215	835	34000	1.92	—	—	—	.00800	1.953	26.8	240
N4B	1/8	.064	.0246	—	—	—	—	—	—	2.0	5.08	18.1	.00800	1.953	—	250

TABLE 2.- DETAILED TEST RECORD

[Rivet diameter, 3/32 in.; plate thickness, 0.064 in.; rivet area, 0.0138 sq in.]

Temperature (°F)	Specimen	Rupture Energy (ft lb)			Fall of pendulum (ft)	Velocity (fps)
		Initial	Final	Lost		
Method C, h_b = -0.003						
70	CA1	4.0	3.2	0.8	0.092	2.44
70	CA2	4.0	3.5	0.5	.092	2.44
70	CA3	4.0	3.4	.6	.092	2.44
70	CA4	4.0	3.25	.75	.092	2.44
70	CA5	4.0	3.4	.6	.092	2.44
Method C, h_b = 0.000						
70	CB1	4.0	3.4	0.6	0.092	2.44
70	CB2	4.0	3.35	.65	.092	2.44
70	CB3	4.0	3.4	.6	.092	2.44
70	CB4	4.0	3.45	.55	.092	2.44
70	CB5	4.0	3.4	.6	.092	2.44
Method C, h_b = 0.010						
70	CC1	4.0	3.5	0.5	0.092	2.44
70	CC2	4.0	3.5	.5	.092	2.44
70	CC3	4.0	3.6	.4	.092	2.44
70	CC4	4.0	3.55	.45	.092	2.44
70	CC5	4.0	3.6	.4	.092	2.44
Method E						
70	NA1	4.0	3.55	0.45	0.092	2.44
70	NA2	4.0	3.6	.4	.092	2.44
70	NA3	4.0	3.7	.3	.092	2.44
70	NA4	4.0	3.6	.4	.092	2.44
70	NA5	4.0	3.6	.4	.092	2.44
Method C, h_b = -0.003						
-67	CA6	3.0	2.0	1.0	0.069	2.11
-67	CA7	3.0	1.95	1.05	.069	2.11
-57	CA8	3.0	2.00	1.00	.069	2.11
-52	CA9	3.0	1.90	1.10	.069	2.11
-66	CA10	3.0	2.00	1.00	.069	2.11
Method C, h_b = 0.000						
-70	CB6	3.0	2.05	0.95	0.069	2.11
-66	CB7	3.0	2.00	1.00	.069	2.11
-66	CB8	3.0	2.00	1.00	.069	2.11
-56	CB9	3.0	2.00	1.00	.069	2.11
-56	CB10	3.0	1.80	1.20	.069	2.11
Method C, h_b = 0.010						
-67	CC6	3.0	2.10	0.90	0.069	2.11
-70	CC7	3.0	2.05	.95	.069	2.11
-70	CC8	3.0	2.05	.95	.069	2.11
-53	CC9	3.0	2.20	.80	.069	2.11
-55	CC10	3.0	2.10	.90	.069	2.11
Method E						
-71	NA6	3.0	2.20	0.80	0.069	2.11
-71	NA7	3.0	2.15	.85	.069	2.11
-70	NA8	3.0	2.10	.90	.069	2.11
-55	NA9	3.0	2.10	.90	.069	2.11
-53	NA10	3.0	2.20	.80	.069	2.11

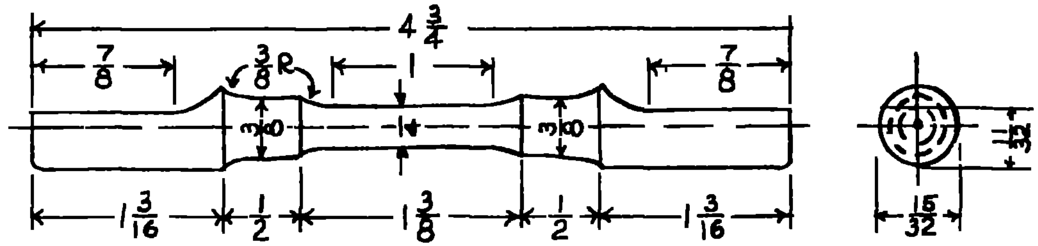
TABLE 3.- TABULATED RESULTS OF IMPACT TESTS ON RIVETED JOINTS

Room-temperature tests[a]		Low-temperature tests		
Specimen	Energy (ft-lb)	Specimen	Temperature (°F)	Energy (ft-lb)
h_b = -0.003				
CA1	0.80	CA6	-67	1.00
CA2	.50	CA7	-67	1.05
CA3	.60	CA8	-57	1.00
CA4	.75	CA9	-52	1.10
CA5	.60	CA10	-66	1.00
h_b = 0.000				
CB1	0.60	CB6	-70	0.95
CB2	.65	CB7	-66	1.00
CB3	.60	CB8	-66	1.00
CB4	.55	CB9	-56	1.00
CB5	.60	CB10	-56	1.20
h_b = 0.010				
CC1	0.50	CC6	-67	0.90
CC2	.50	CC7	-70	.95
CC3	.40	CC8	-70	.95
CC4	.45	CC9	-53	.80
CC5	.40	CC10	-55	.90
Method E				
NA1	0.45	NA6	-71	0.80
NA2	.40	NA7	-71	.85
NA3	.30	NA8	-70	.90
NA4	.40	NA9	-55	.90
NA5	.40	NA10	-53	.80

[a]Room temperature, 70° F

TABLE 4.- TORSION IMPACT TESTS OF SUPPLEMENTARY SPECIMENS OF ALUMINUM ALLOY 17S-T

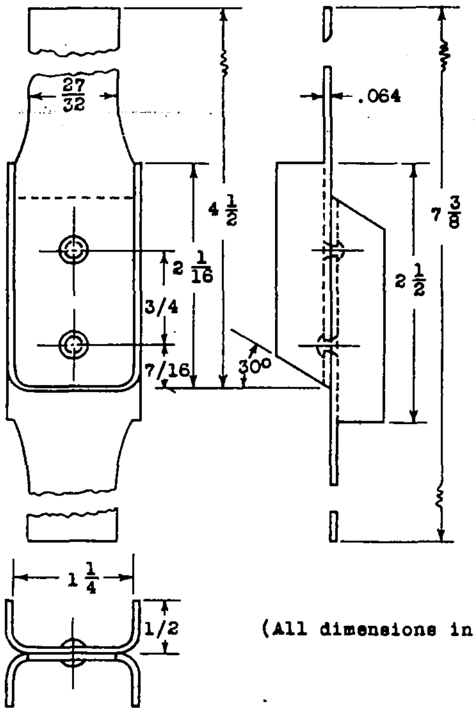
[Material cut from ½-in. round rod obtained from commercial warehouse in Chicago in 1940]



Standard Specimen

Specimen	Temperature (°F)	Dimensions: Length (in.)	Dimensions: Diameter (in.)	Dimensions: Volume (cu in.)	Initial (a) kinetic energy: Speed (rpm)	Initial (a) kinetic energy: Energy (ft-lb)	Final (b) kinetic energy: Speed (rpm)	Final (b) kinetic energy: Energy (ft-lb)	Energy of rupture	Modulus of toughness (c)
1	70	1.02	0.249	0.0497	600	91.08	380	36.73	54.35	1084
2	70	1.02	.249	.0497	600	91.08	390	38.71	52.37	1053
3	70	1.02	.2465	.0486	600	91.08	380	36.73	54.35	1119
										Av. 1085
4	-70	1.08	0.2495	0.0528	600	91.08	330	27.70	63.38	1200
5	-70	1.04	.2494	.0508	600	91.08	350	31.17	59.91	1180
6	-70	1.05	.2505	.0517	600	91.08	340	29.40	61.68	1194
7	-70	1.07	.2498	.0524	600	91.08	335	28.55	62.53	1194
										Av. 1192

[a] Striking energy = 0.000253 x (rpm)^2.
[b] Remaining energy = 0.000254 x (rpm)^2.
[c] Toughness ratio = $\frac{1192}{1085}$ = 1.10.



Speci-men	Rivet diameter (in.)	Rivet-head angle (deg)	h_b	Method of driving	Depth of counter-sink	Number req'd.
CA1 to CA24	3/32	78	-0.003	C	0.050	24
CB1 to CB24	3/32	78	.000	C	.047	24
CC1 to CC24	3/32	78	.010	C	.037	24
NA1 to NA24	3/32	60	--	Reverse	.030	24

Figure 1.- Details of specimens for main tests.

(All dimensions in inches)

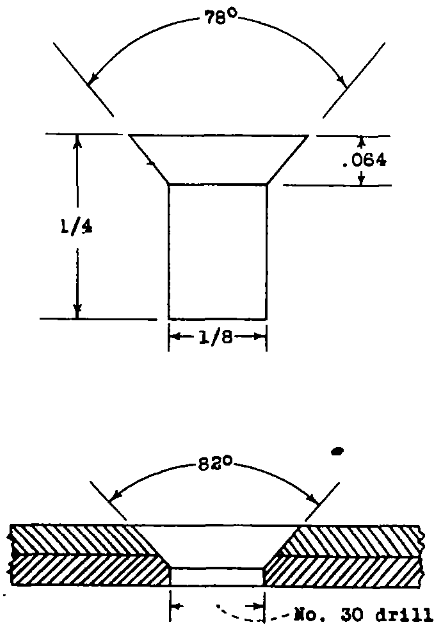


Figure 2.- Dimensions of machine-countersunk rivet and angle of countersink used in riveting method C for 1/8-in. rivet.

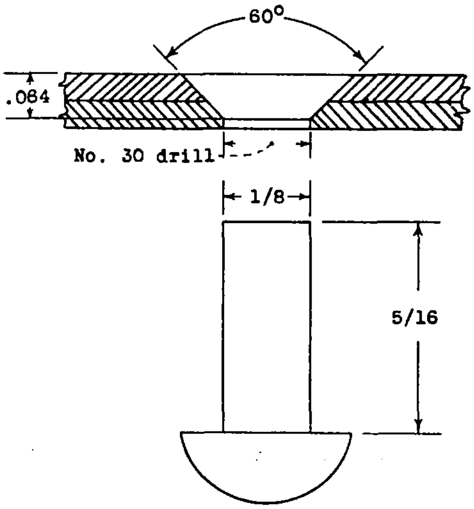


Figure 3.- Dimensions of roundhead rivet and angle of countersink used in riveting method E for 1/8-in. rivet.

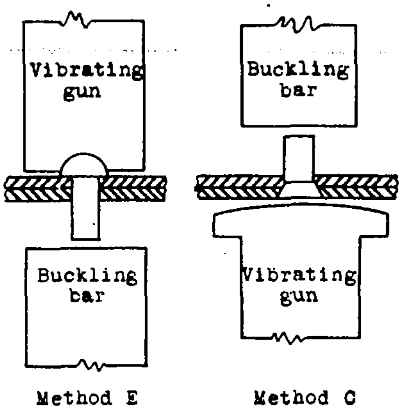


Figure 4.- Methods of riveting used in this investigation.

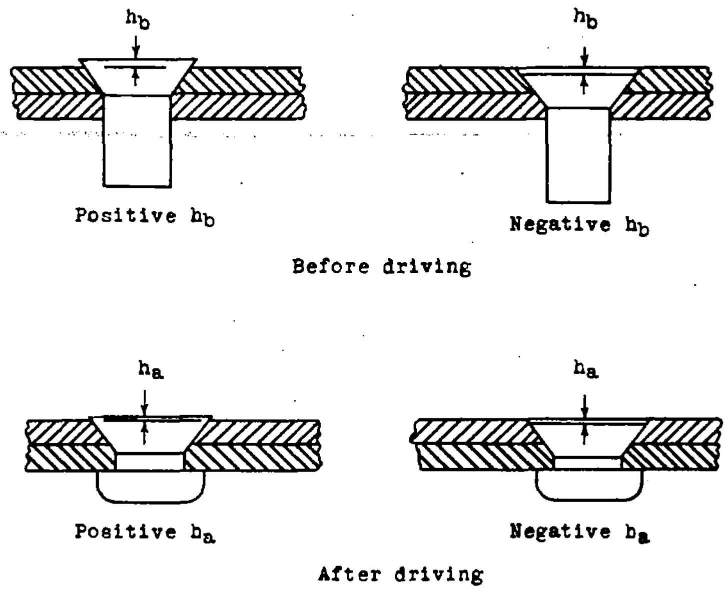
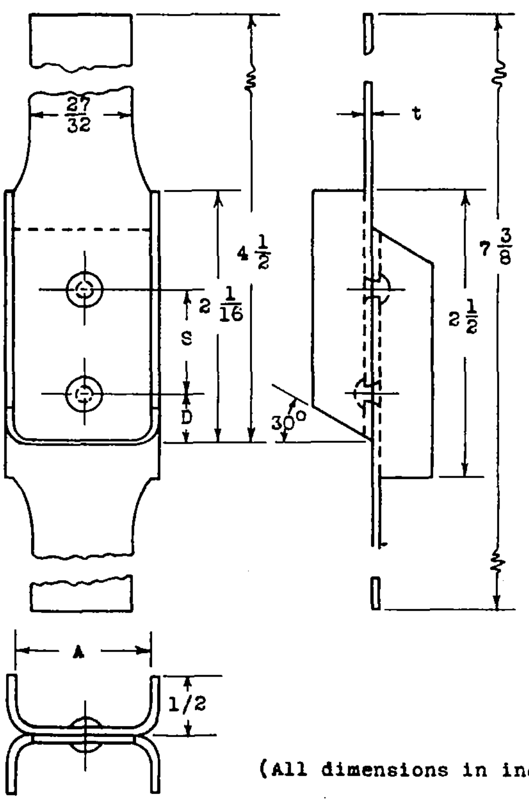


Figure 5.- Illustrations of h_b and h_a for machine-countersunk rivets.



Specimen	Rivet diameter d (in.)	Sheet thickness t (in.)	S (in.)	D (in.)	A (in.)	Depth of countersink
Method C; h_b = 0; rivet-head angle, 78°						
C1A C1B	3/32	0.040	3/4	7/16	1-1/8	0.047
C2A C2B	3/32	.064	3/4	7/16	1-1/4	.047
C3A C3B	1/8	.040	7/8	3/8	1-1/8	.060
C4A C4B	1/8	.064	7/8	3/8	1-1/4	.060
Method E; rivet-head angle, 60°						
N1A N1B	3/32	0.040	3/4	7/16	1-1/8	0.030
N2A N2B	3/32	.064	3/4	7/16	1-1/4	.030
N3A N3B	1/8	.040	7/8	3/8	1-1/8	.050
N4A N4B	1/8	.064	7/8	3/8	1-1/4	.050

(All dimensions in inches)

Figure 6.- Details of specimens for preliminary tests.

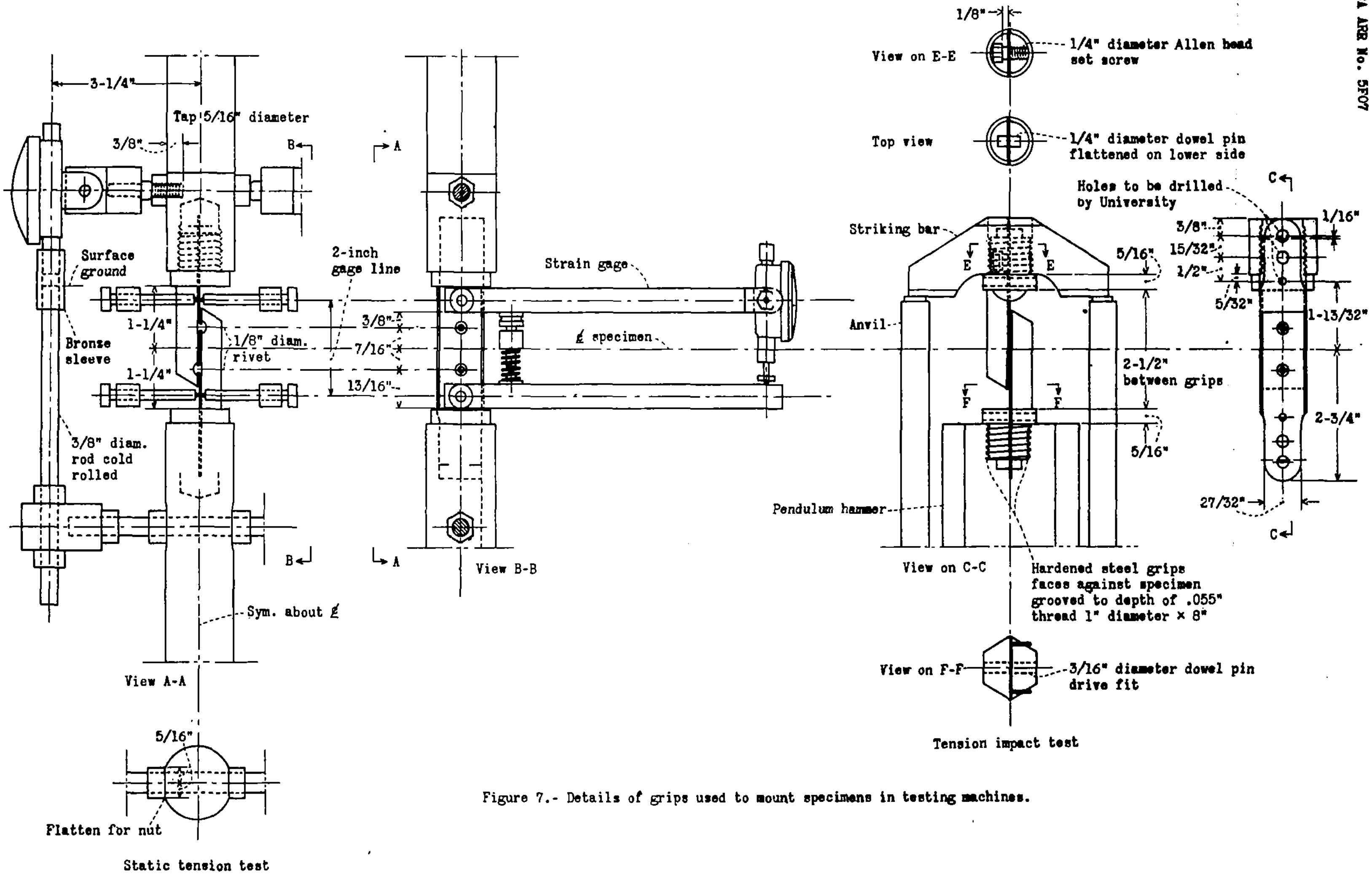


Figure 7.- Details of grips used to mount specimens in testing machines.

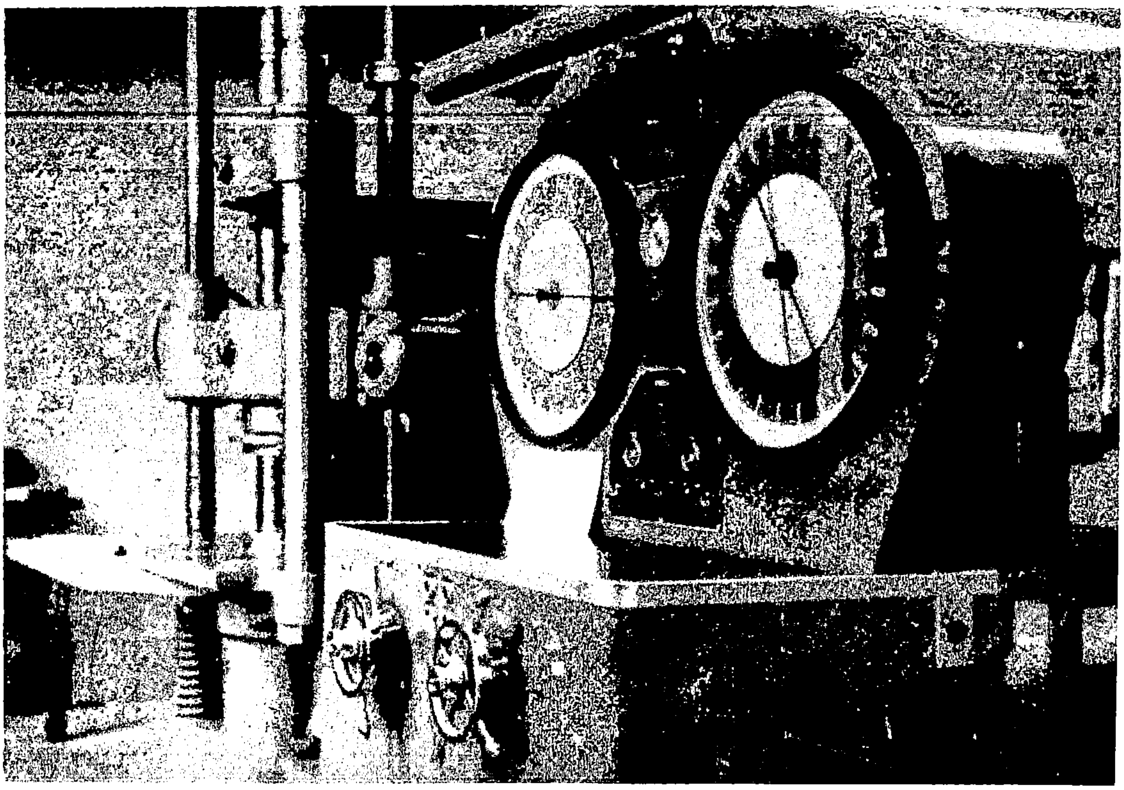


Figure 8.—Southwark-Emery hydraulic testing machine.

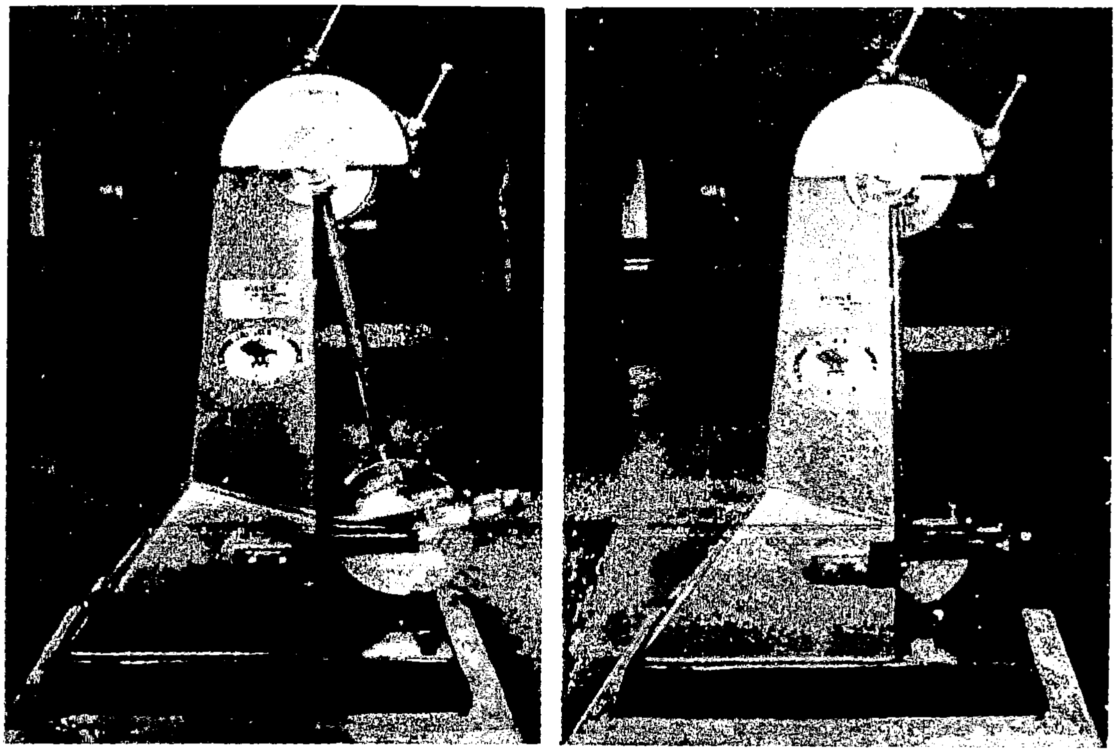


Figure 9.—Riehle pendulum impact machine.

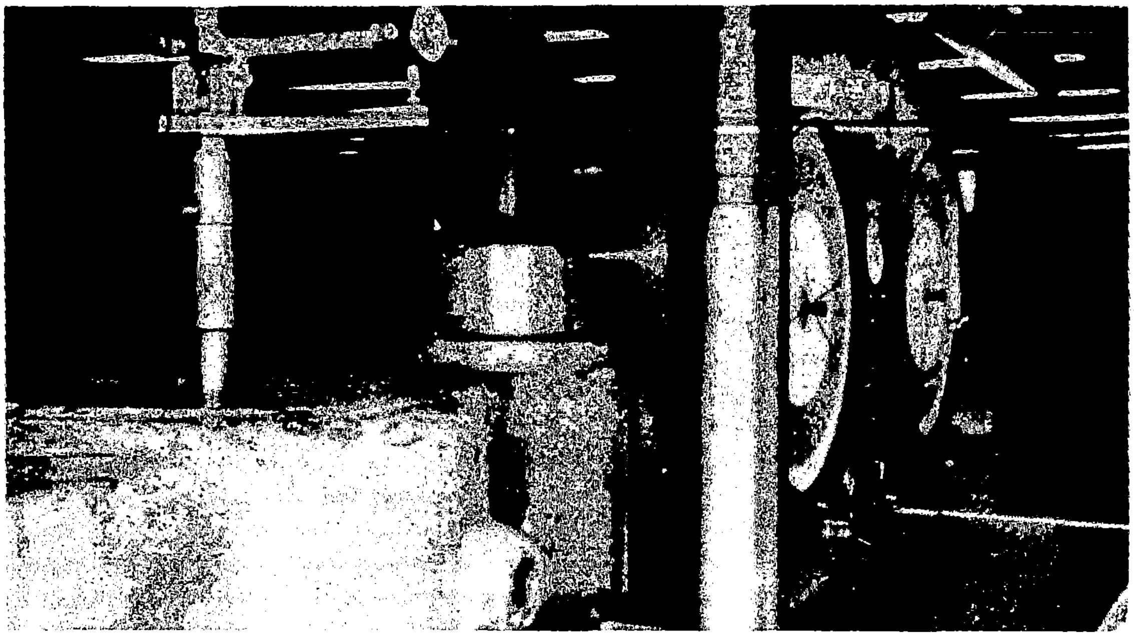


Figure 10.—Specimen mounted in static testing machine.

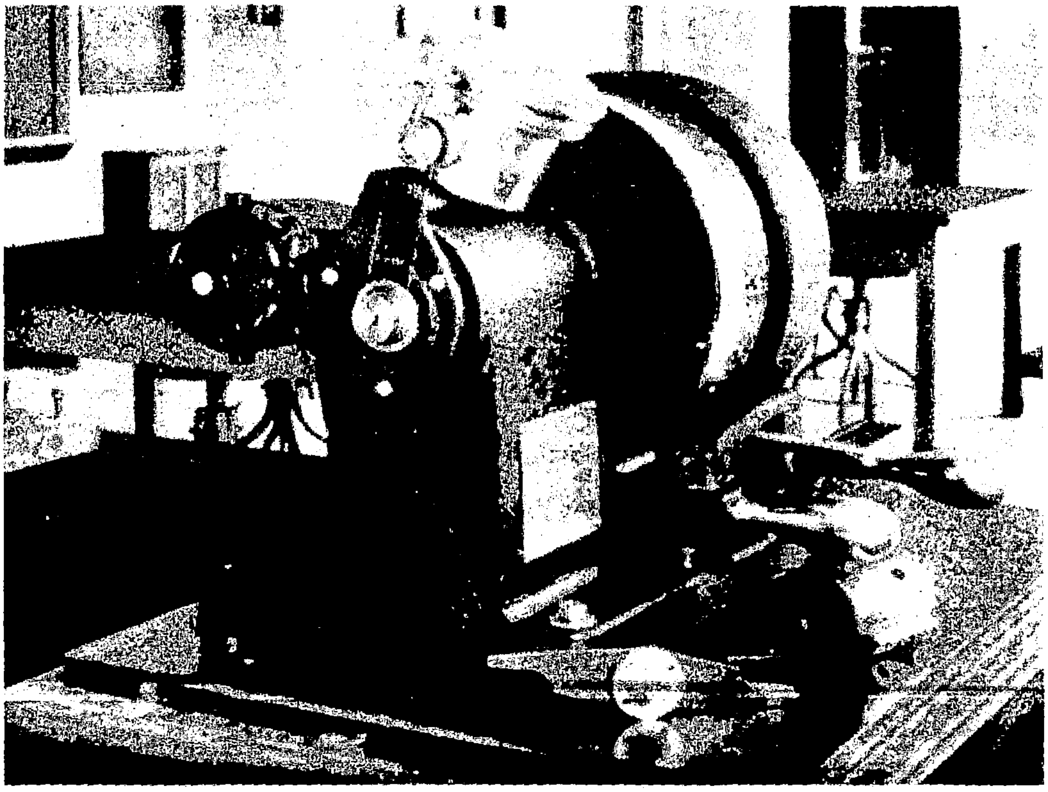
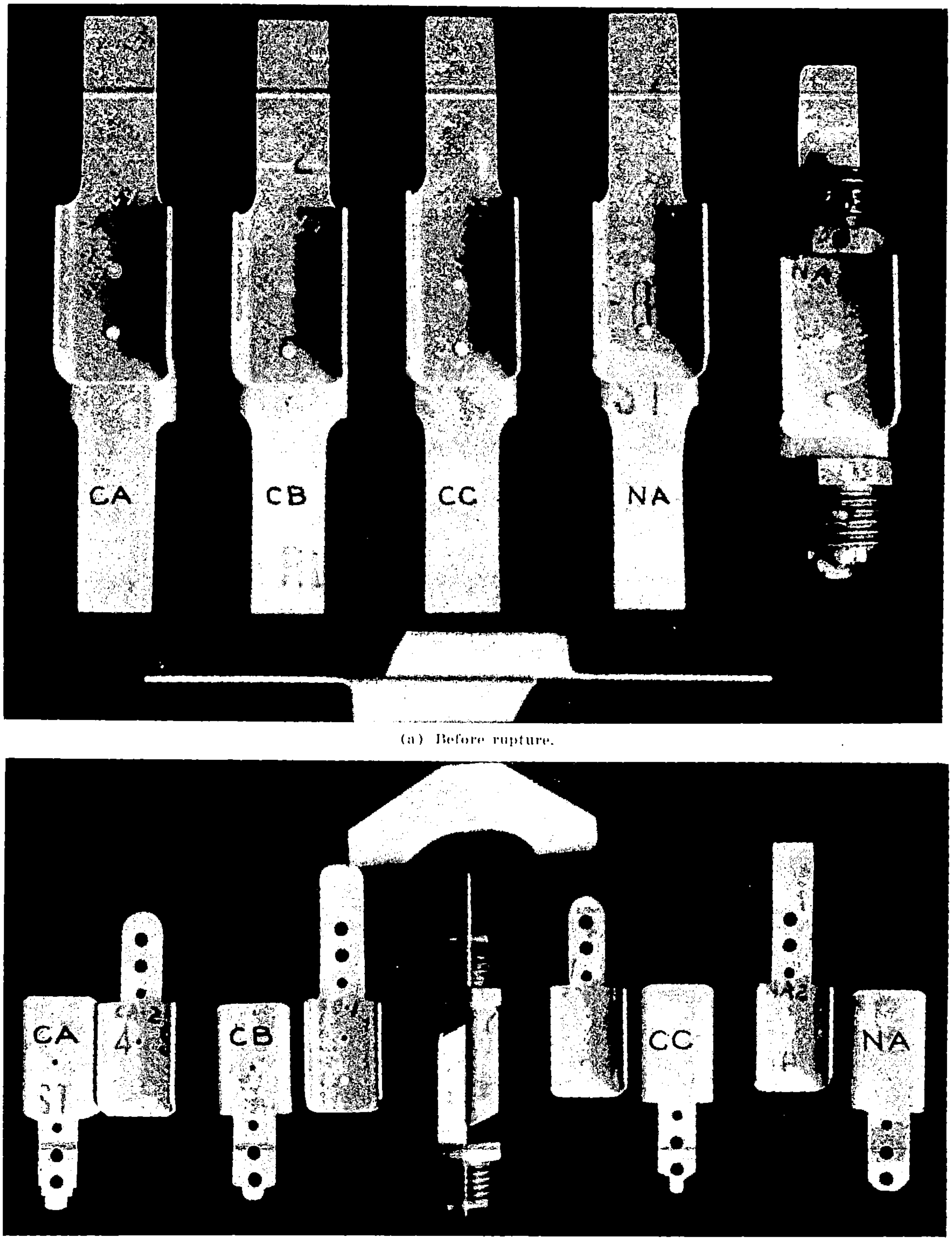


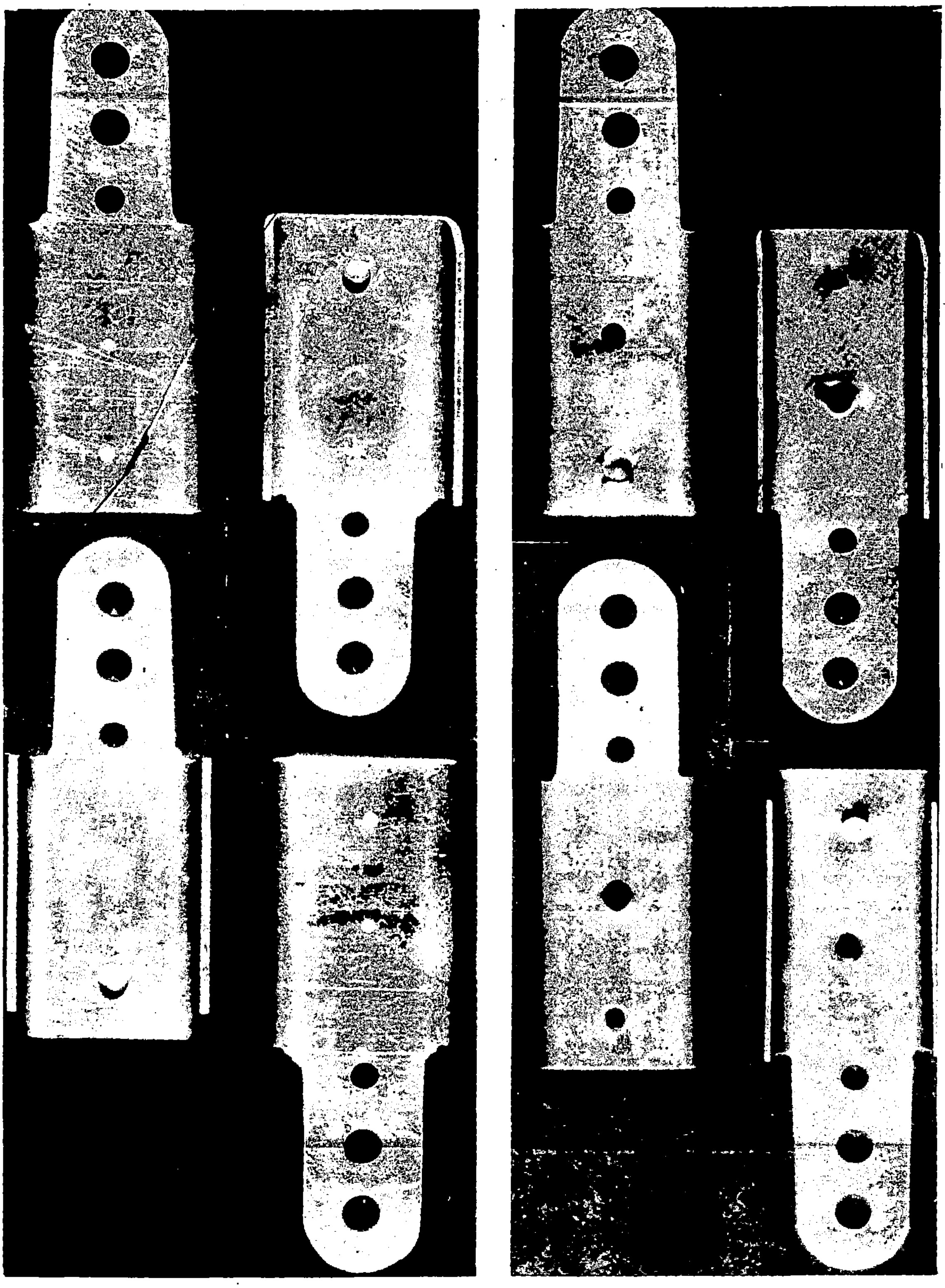
Figure 24.—Carpenter torsion impact machine.



(a) Before rupture.

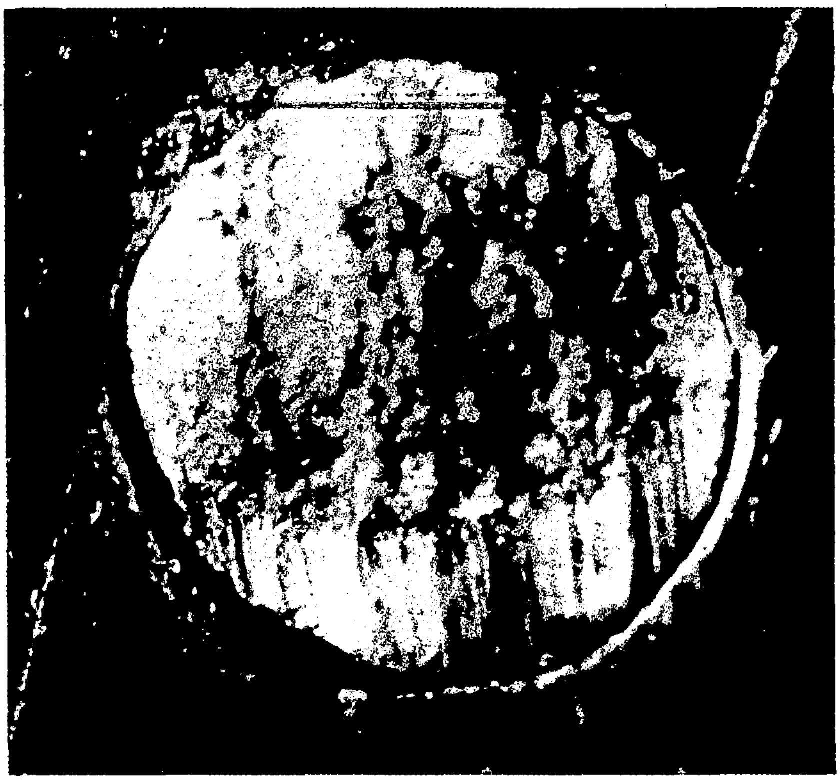
(b) After rupture.

Figure 11.—Test specimens CA, CB, CC, and NA.



(a) Specimens N2A (b) Specimens C3B

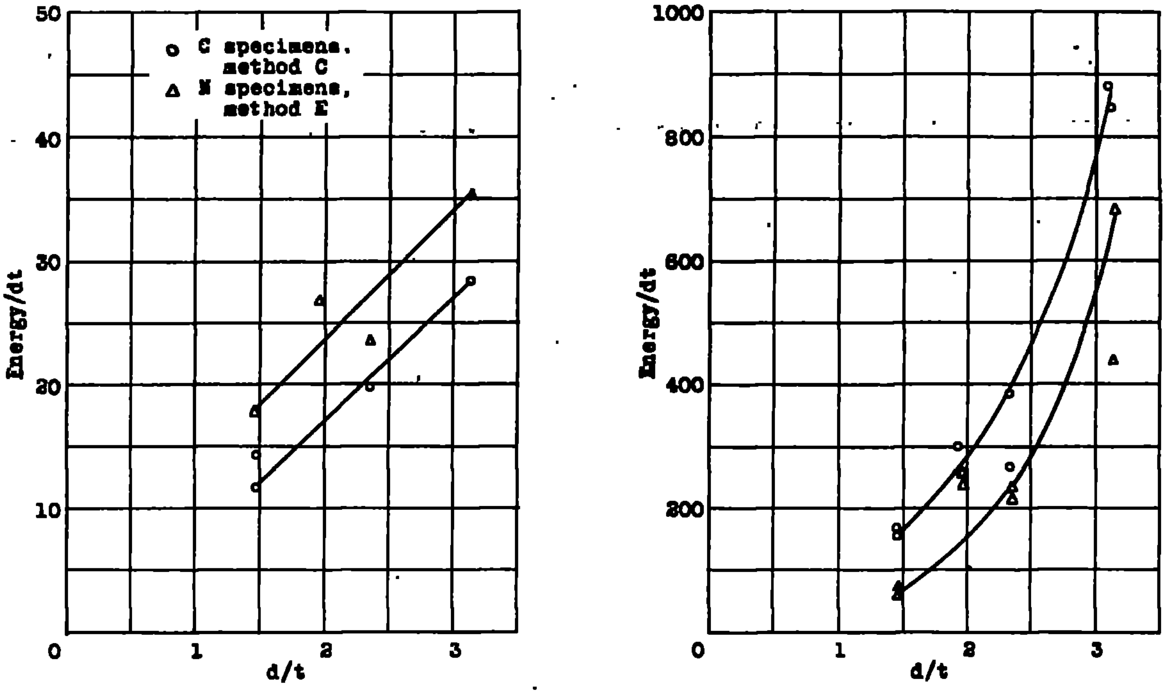
Figure 12.—Preliminary-test specimens N2A and C3B after rupture.



(a) Rivet diameter, 1/8-inch; plate thickness, .040-inch

(b) Rivet diameter, 5/32-inch; plate thickness, .064-inch.

Figure 13.—Preliminary-test rivets after failure, enlarged.



(a) Energy to yield load

(b) Energy to rupture

Figure 14.- Energy to yield load and to rupture for specimens in preliminary tests; h_b = 0.

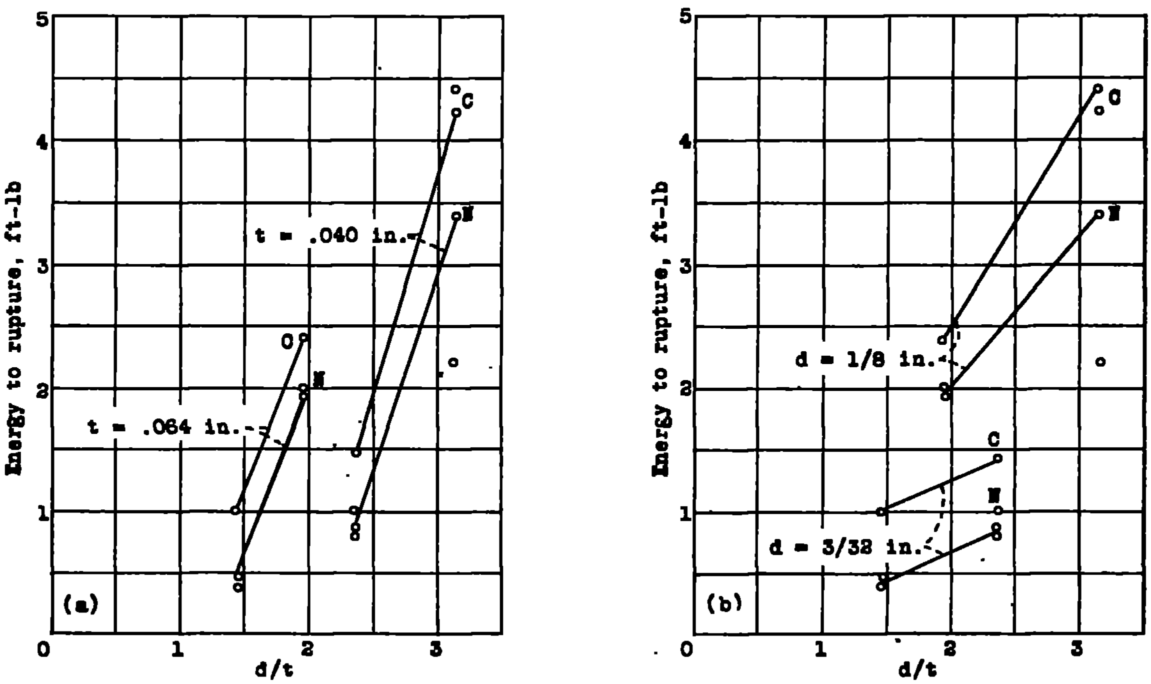


Figure 15.- Static and dynamic loads of specimens C and N in preliminary tests.

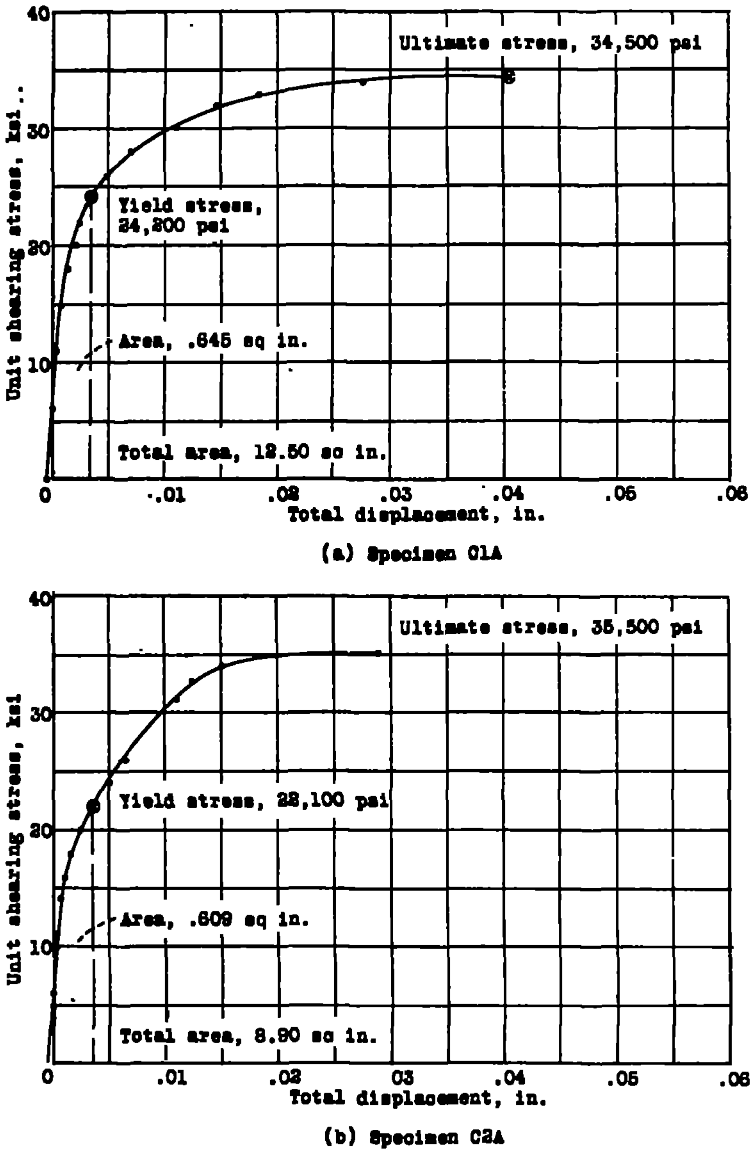


Figure 16.- Static stress-strain curves for specimens C1A and C2A.

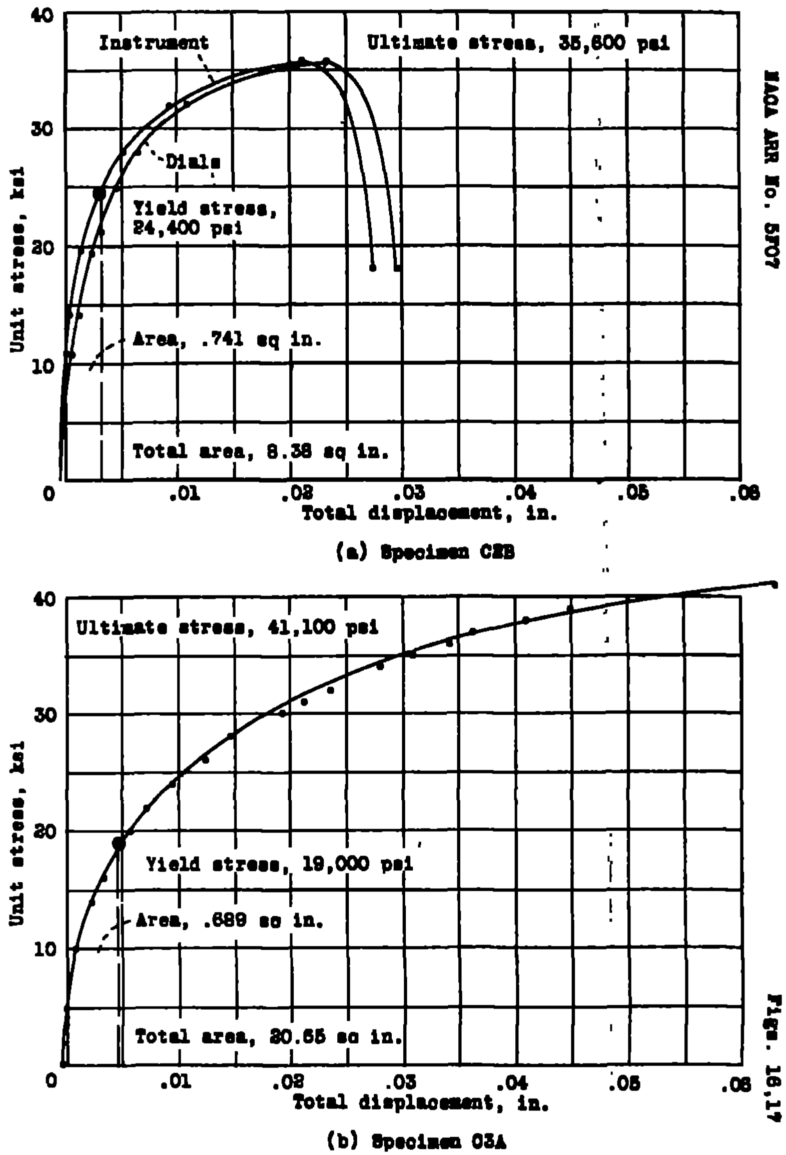
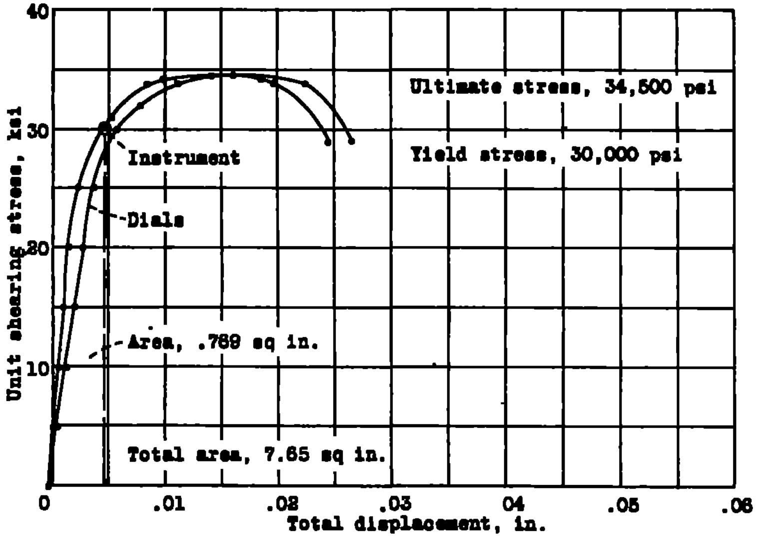
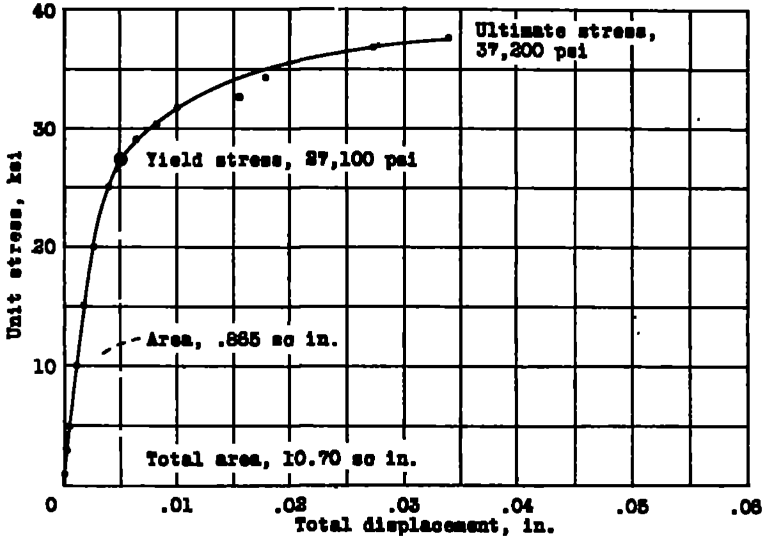


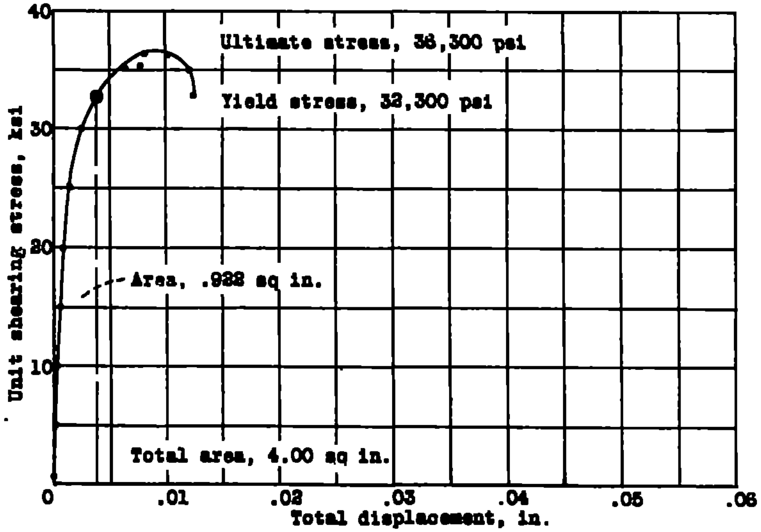
Figure 17.- Static stress-strain curves for specimens C2B and C3A.



(a) Specimen N1A

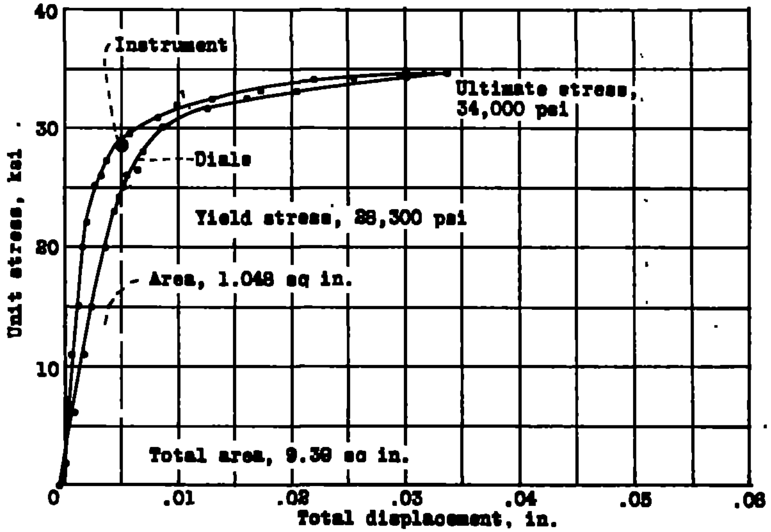


(a) Specimen N3A



(b) Specimen N2B

Figure 18.- Static stress-strain curves for specimens N1A and N2B.



(b) Specimen N4A

Figure 19.- Static stress-strain curves for specimens N3A and N4A.

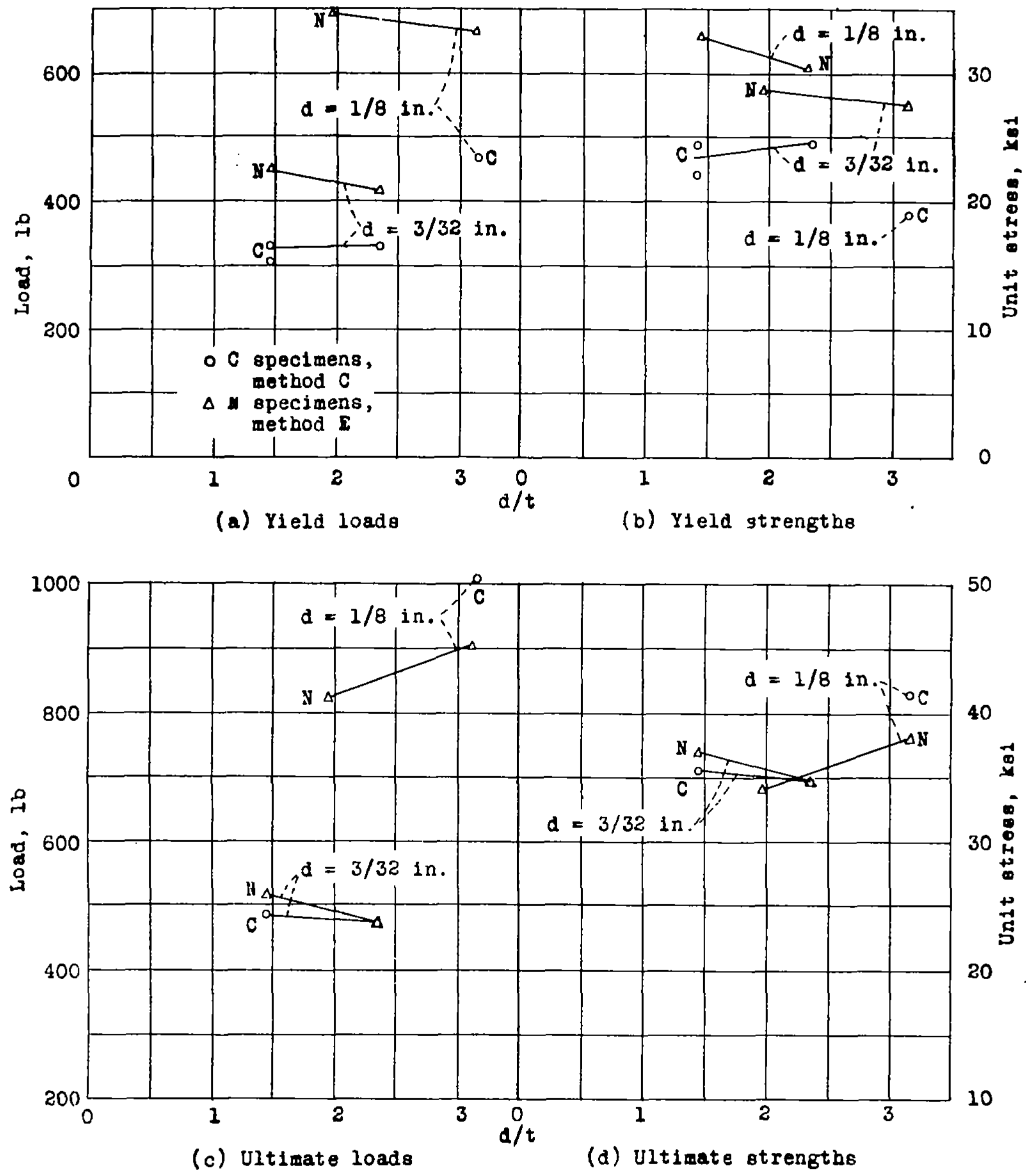


Figure 20.- Yield and ultimate loads and strengths for C specimens riveted by method C and N specimens riveted by method E.

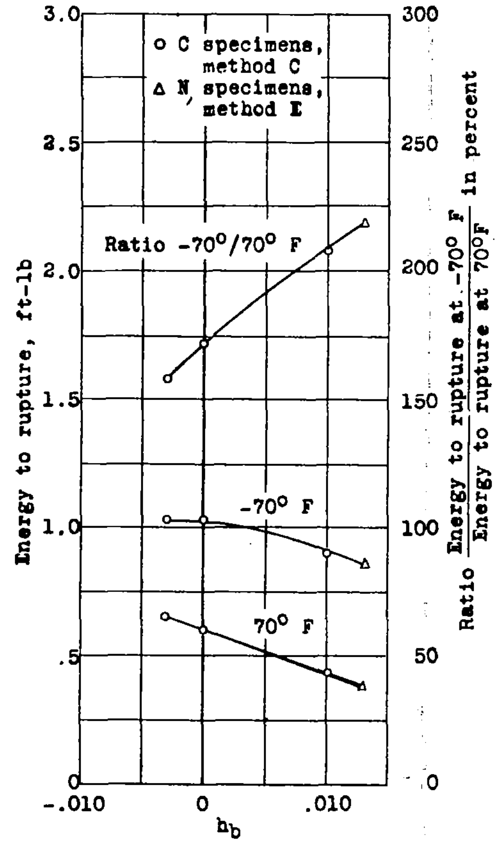
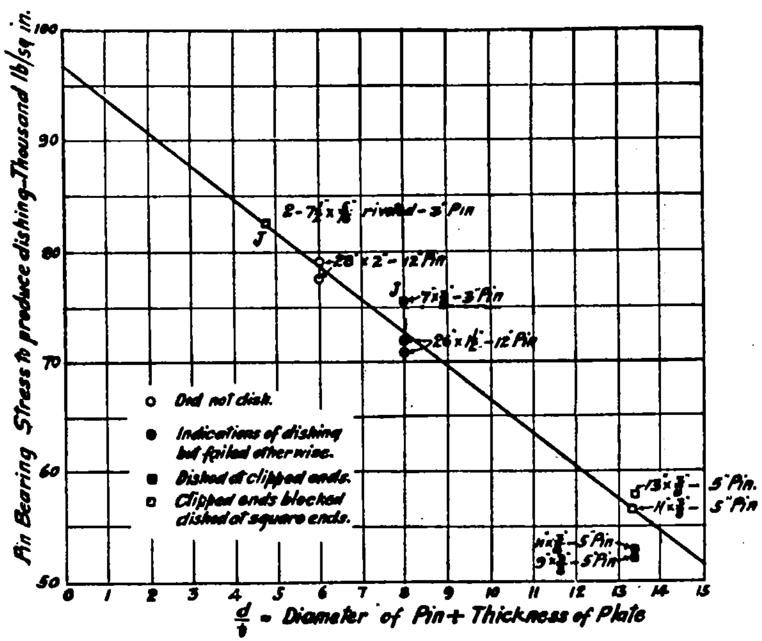


Figure 23.- Energy of rupture for specimens in main tests. d/t = 1.46.

(a) Quebec Bridge hangers. (From reference 6, p. 139.)



(b) Graph of buckling tests on hanger pin plates. (From reference 6, p. 227.)

Figure 21.—Buckling tests on Quebec hanger plates (reference 6).

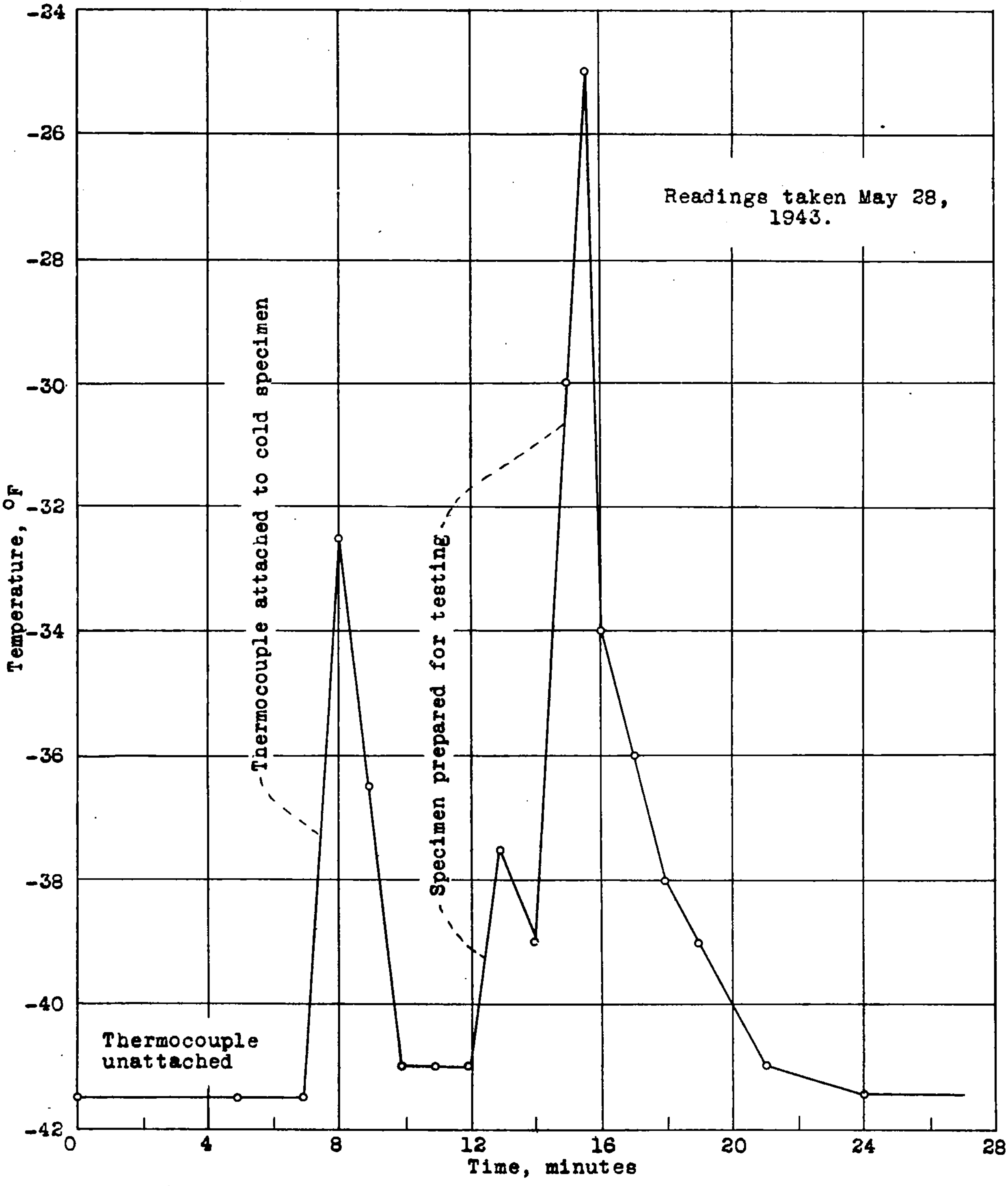
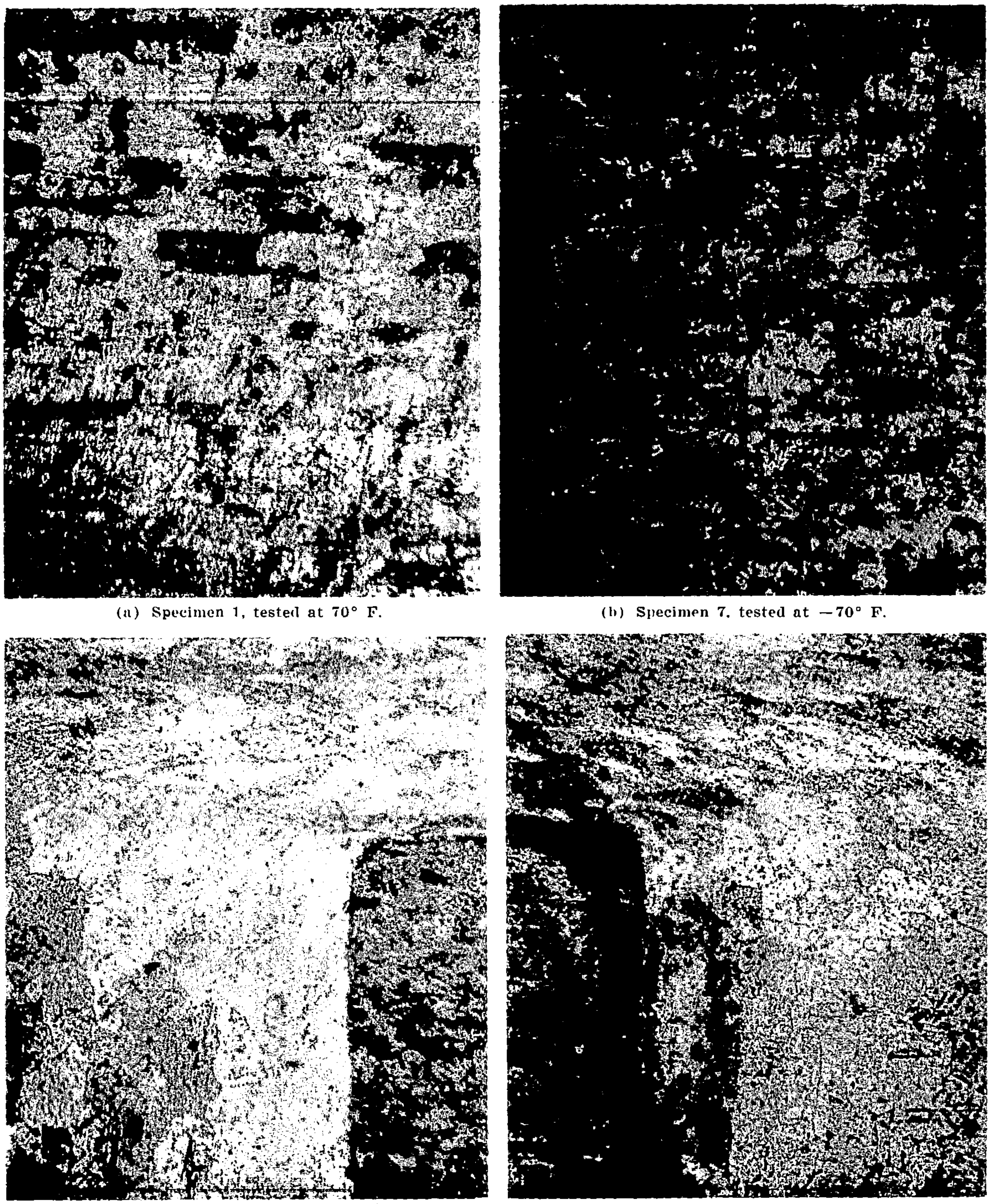


Figure 22.- Thermocouple record of effect of handling riveted test specimens in cold rooms.



(a) Specimen 1, tested at 70° F.

(b) Specimen 7, tested at −70° F.

(c) Specimen CC5, tested 70° F.

(d) Specimen CC8, tested at −70° F.

Figure 25.—Photomicrographs of specimens tested at 70° and −70° F.